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Remote Sens. **2011**, *3*, 708-720; doi:10.3390/rs3040708

OPEN ACCESS

Remote Sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

The Relevance of GLAS/ICESat Elevation Data for the Monitoring of River Networks

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Received: 25 January 2011; in revised form: 23 March 2011 / Accepted: 29 March 2011 / Published: 6 April 2011

Abstract: The Ice, Cloud and Land Elevation Satellite (ICESat) laser altimetry mission from 2003 to 2008 provided an important dataset for elevation measurements. The quality of GLAS/ICESat (Geoscience Laser Altimeter System) data was investigated for Lake Leman in Switzerland and France by comparing laser data to hydrological gauge water levels. The correction of GLAS/ICESat waveform saturation successfully improved the quality of water elevation data. First, the ICESat elevations and waveforms corresponding to water footprints across the transition from the land to water were analyzed. Water elevations (2 to 10 measurements) following the land-water transition are often of lesser quality. The computed accuracy for the ICESat elevation measurements is approximately 5 cm, excluding transitions footprints, and 15 cm, including these footprints. Second, the accuracy of ICESat elevation was studied using data acquired on French rivers with a width greater than the size of the ICESat footprint. The obtained root mean square error (RMSE) for ICESat elevations in regard to French rivers was 1.14 m (bias = 0.07 m; standard deviation = 1.15 m), which indicates that small rivers could not be monitored using ICESat with acceptable accuracy due to land-water transition sensor inertia.

Keywords: lidar; ICESat; rivers; lakes; elevation

1. Introduction

Freshwater provisioning will be a major problem in future decades. Currently, 1 billion people depend on lakes for domestic water consumption, which will expand to 5.5 billion in 30 years [1]. Monitoring of continental water resource, particularly lakes and rivers, is necessary because many global regions lack sufficient water for domestic consumption, agriculture, and other uses. Hydrologic networks that are generally organized on a national basis provide monitoring of water resource. These networks measure the temporal variations in the water level of rivers, lakes and reservoirs. However, the spatial distribution of hydrological gauges is insufficient in some parts of the world due to freshwater needs. Moreover, a reduction in the number of stations has been observed in conjunction with a decline in the quality of measurements. A better understanding of the global water cycle and the impact of climate change requires a thorough knowledge of water resources on the continental surface. Therefore, there is a real demand for a global, homogeneous, perennial monitoring system of continental water.

Optical and Synthetic Aperture Radar (SAR) imageries (e.g., LANDSAT, NOAA, MODIS, SPOT, ASTER, ERS, ASAR, RADARSAT, and PALSAR/ALOS) are often used to map the extent of water areas [2,3]. Determination of changes in the associated water level is estimated using radar altimeters and lidar systems [4-6]. The radar altimetry missions demonstrated the potential of continental water observation with three principal advantages suitable to hydrological observations: all-weather operability, global data coverage, and temporal repetivity (10 days for Jason and Topex and 35 days for ENVISAT and ERS). The radar altimeters used for Topex/Poseidon, ERS-2, ENVISAT, and Jason-1/2 have a coarse spatial resolution "footprint size" (a few hundred meters to few kilometers), which means they can monitor only large lakes, rivers, and reservoirs. Typically, altimetric measurements can range in accuracy from a few centimeters (e.g., Great Lakes, USA) [7,8] to tens of centimeters (e.g., Lake Chad, Africa) [8]. Accuracies of 5 cm RMS for Lake Issykkul (Kirgyzstan) and 10 cm RMS for Lake Chardarya (Kazakhstan) were previously determined by Crétaux and Birkett [9]. In all of these studies, the obtained accuracies are directly related to the size of the body of water because the satellite measurement compared to ground reality is usually obtained by averaging individual shot measurement along tracks. Therefore, rivers appear more difficult to study because of their width. The first studies relating to rivers were performed in the Amazonian basin, which contains very large rivers. In studies by Birkett *et al.* [5], RMSE (Root Mean Square Error) values between hydrologic gauges and Topex/Poseidon data for a selection of rivers and floodplains in the Amazon Basin exhibited high variability, with an overall mean of approximately 1.1 m RMS and optimal values of approximately 40 cm. The accuracy for rivers is highly variable, being that these measurements are dependent on the target width.

Satellite laser altimetry, such as the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and Land Elevation Satellite (ICESat), provides elevation data that are very useful to many applications and offer the potential to monitor small water areas due to small associated footprints (50 to 90 m). NASA launched the ICESat satellite in January 2003 [10,11]. ICESat includes two laser altimeters operating at visible (green, 532 nm) and near-infrared (1,064 nm) wavelengths, and each near-infrared laser footprint along the satellite track is 172 m apart, with 40 points (shots) per second (40 Hz). The horizontal geolocation accuracy of the ICESat footprints is 3.7 m. The waveform of each shot is sampled in 544 or 1,000 bins over land area at a temporal resolution of 1 ns. The vertical resolution of land waveforms is 15 cm. The nominal pointing angle of ICESat is approximately 0.3° off nadir, with a potential of up to 5°. The high pointing angles reduce the specular reflection on waters, and therefore, the waveform saturation will increase the elevation error [12]. However, GLAS laser altimeter cannot be used for routine monitoring because only some tracks are possible with ICESat due to power safety and meteorological conditions, which is in contrast to radar altimeters where study sites are revisited every 10 days.

Chipman and Lillesand [13] assessed the accuracy of the ICESat GLAS laser altimeter on the Toshka lakes west of Lake Nasser in southern Egypt. The standard deviation of GLAS elevation measurements along a single transect was on the order of 3–8 cm. Bhang *et al.* [14] have demonstrated a difference between GLAS elevation and gauging stations between 2 and 35 cm for lakes in Otter Tail County, Minnesota (USA). Other studies have demonstrated that the accuracy of ICESat is greater than 10 cm, compared to gauge data [12,15,16]. However, the quality of ICESat data for rivers has not been thoroughly investigated. Analysis of ICESat measurements (transect of 50 km with 300 footprints/shots) along the Tapajos River, Brazil, provides a RMSE of approximately 3 cm for clear meteorological conditions, 8 to 15 cm for partly cloudy skies, and 25 cm for heavy clouds [12]. These studies are indicative of the performance of ICESat for large-size targets, with high spatial coverage. The accuracy of lidar measurements should be degraded for small targets, with only some measurements by track, as in Birkett *et al.* [5], where a factor of ten was observed with radar altimetry between RMSE obtained from rivers and floodplains. Could the elevation of rivers and lakes that span several hundreds of meters be measured with good accuracy (approximately 10 cm) using ICESat (footprints of 50–90 m)?

Moreover, the number of measurements excluded from each ICESat transect corresponding to footprints with possible disturbances related to the land-water transition is never specified. However, the value of this margin will limit the size of targets that could be analyzed by laser systems, such as ICESat.

The response of GLAS/ICESat to the land-water transition was first analyzed. The accuracy of ICESat for Lake Leman (a flat surface) was then evaluated. Finally, the potential use of ICESat measurements for rivers in France (small targets) was studied.

2. Lake Leman

2.1. Description of Study Site and Dataset

Study Site

The accuracy of ICESat measurements was evaluated across Lake Leman located in Switzerland and France (Lat. 46°26′N and Long. 6°33′E). This is one the largest lakes in Western Europe with a surface of 582 km^2. The average level of water is 372 m, which is controlled by the Seujet Dam near Geneva. The maximum length and width of the lake are 73 and 14 km, respectively.

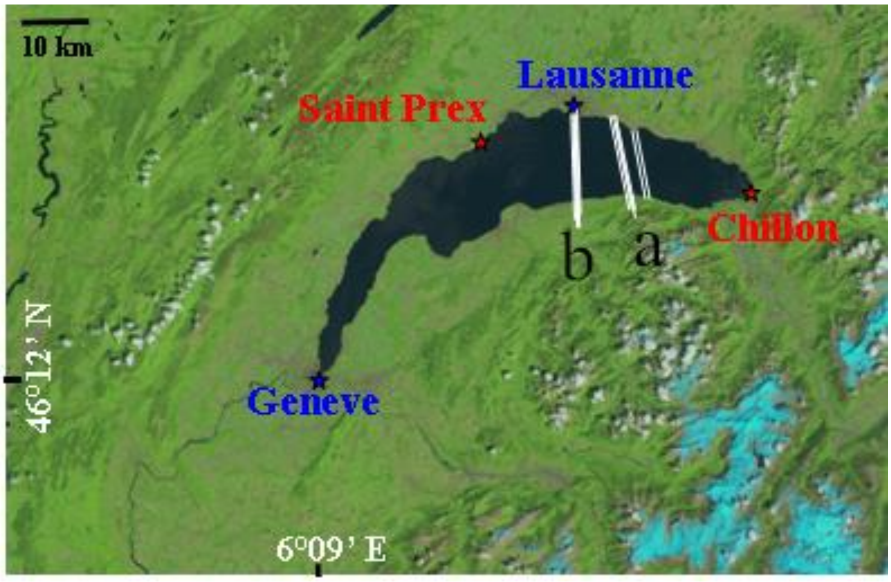
Lake Leman is bordered on the south by the Haute-Savoie massif. The land-water transition in the ascending acquisition mode of ICESat involves a difference in elevation of 550 m for a distance of

5 km (south to north). In the area north of Lausanne, the land-water transition (north to south) in descending mode is softer with a difference in elevation of 260 m for a distance of 5 km.

Dataset

A total of 21 GLAS (Geoscience Laser Altimeter System) transects across Leman Lake were available for comparison with the lake gauge data (Figure 1). ICESat data were acquired between 2 March 2004 and 13 March 2008. The length of transects varied between 8.5 and 10.5 km, with a total number of 774 shots measured. The data used are comprised of GLA01 (waveform) and GLA14 (Land Surface Altimetry) products in the Release 31. The elevation of GLAS laser data was computed using tools developed by the US National Snow and Ice Data Center (NSIDC). Six transects corresponding to cloudy episodes were next excluded from the dataset because the corresponding elevations were strongly disturbed (heights of approximately 3,500 m).

Figure 1. The Ice, Cloud and Land Elevation Satellite (ICESat) tracks through Lake Leman. **(a)** Ascending mode and **(b)** descending mode.



Two hydrological stations, Chillon and Saint Prex (Figure 1), were used to evaluate the accuracy of ICESat elevations. As the difference in water level between the two stations is relatively weak (~1 cm), an average elevation was used. The Swiss Federal Office for the Environment (FOEN) [17] measures water levels at permanent gauging stations for Swiss bodies of water. The water levels of hydrological stations are given in the Swiss height measurement reference system. The reference for all height measurements in Switzerland is the "Repère Pierre du Niton" in the harbor of Geneva (stone). The height of this stone was evaluated in 1902 to be 373.6 m over sea level.

All heights refer to the same vertical datum to conduct a consistent comparison among the two height data sets. In this study, the data comparison was performed in terms of orthometric heights with respect to the WGS84 reference system and the EGM96 geoid model. ICESat elevations available to users correspond to ellipsoidal heights with reference to the Topex ellipsoid. The conversion of the Topex ellipsoid to the WGS84 ellipsoid was approximated by $h_{WGS84} = h_{Topex} - 70.7$ cm. Next, ellipsoidal elevations (h_{WGS84}) were converted into orthometric elevations (H) by applying the EGM96 geoid value (N): $H = h_{WGS84} - N$.

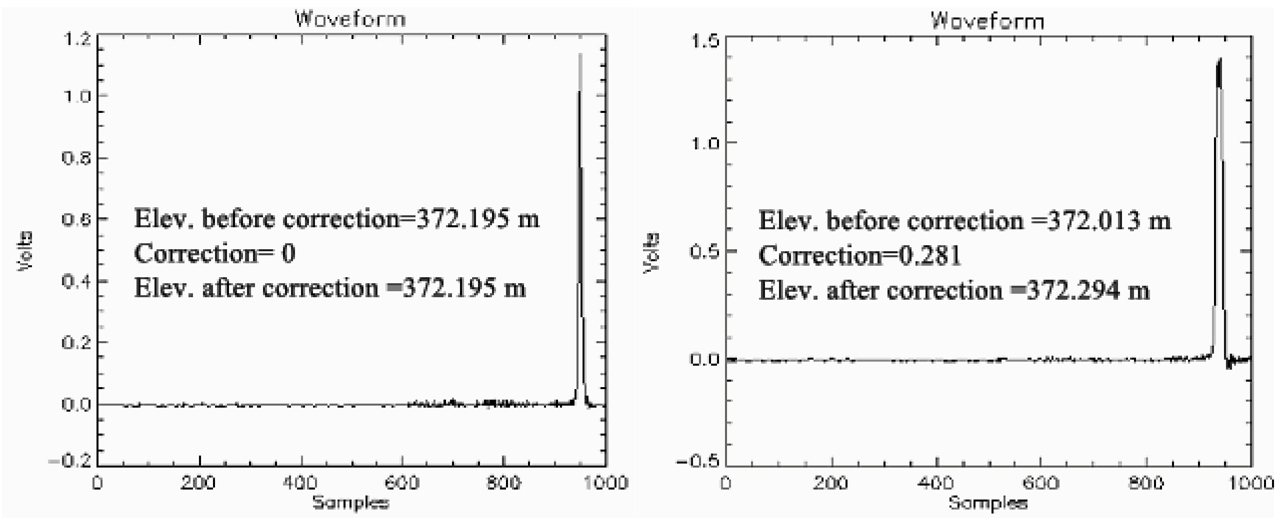
Shots of water were then extracted individually track by track, and the mean elevation was calculated for each track. This mean was used for comparison with reference elevations (hydrological gauges).

2.2. Results

Analysis of ICESat waveforms demonstrated a saturation phenomenon, which must be corrected. Saturation occurs when the returned energy by a number of 1 ns bins is greater than the threshold function of gain [12,18]. Therefore, elevations calculated from saturated waveforms are incorrect. A saturation correction is available for the produced data and is recommended for use on calm waters because of the associated specular reflection. The correction value varies between 0 and 1.5 m and is added to the GLAS elevation. However, the correction is not available for some shots and the value "–999.00" is given instead (*i.e.*, elevation should be corrected, but the method used to calculate the correction coefficient cannot provide a correct value). Figure 2 shows some GLAS waveforms obtained for Lake Leman in the case of water only. For the saturated waveforms (calm water), the high level of reflected energy involves a clipping of the maximum peak, which shifts this peak several bins to the left. The derived GLAS elevation is thus underestimated.

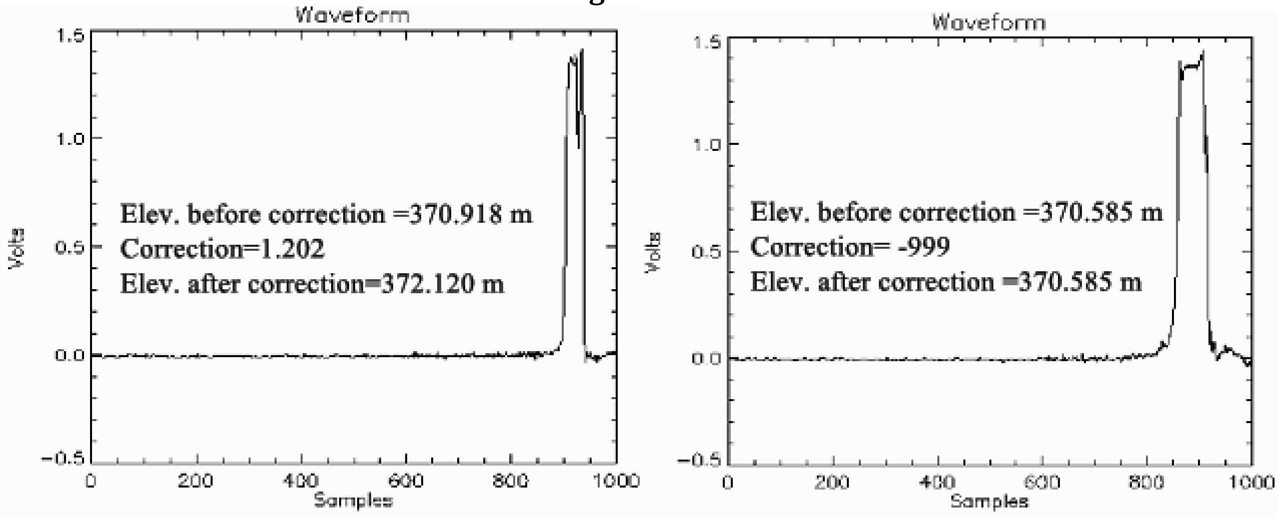
Figure 3 shows the ICESat elevations across Lake Leman for the 3 June 2005 transect. This example shows the importance of the saturation effect (errors reach 1.41 m) and demonstrates the need to include the saturation correction.

Figure 2. Typical Geoscience Laser Altimeter System (GLAS) waveforms on Lake Leman (water only). (**a**) Unsaturated waveform, (**b**) waveform slightly saturated, and (**c**, **d**) waveforms with high saturation. These examples are extracted from the 03 June 2005 transect. The reference elevation is 372.18 m. Ordinate = energy in volts and abscissa = bin number (bin spacing = 1 ns).



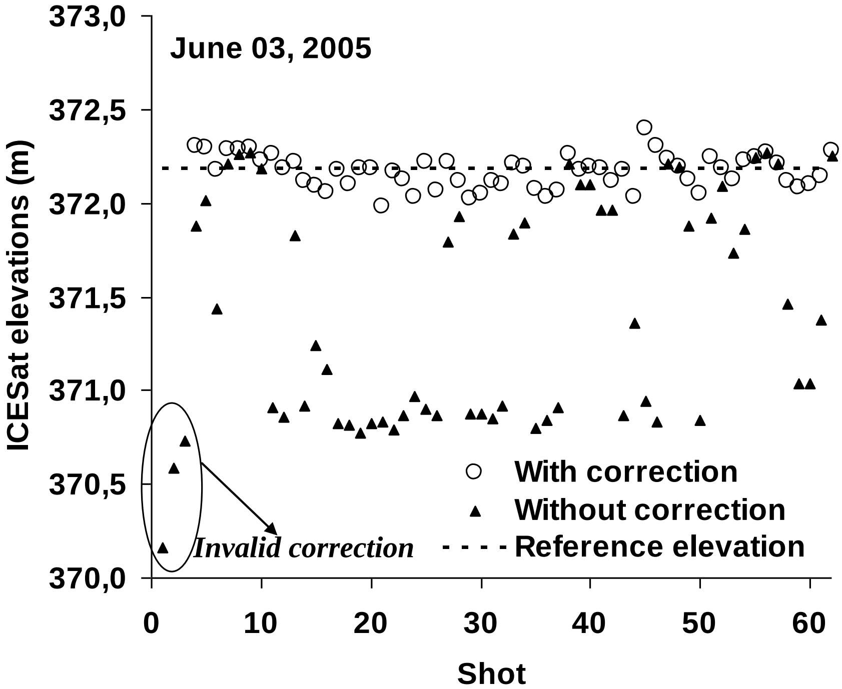
(a) **(b)**

Figure 2. *Cont.*



(c) **(d)**

Figure 3. ICESat elevations across Lake Leman extracted from the 3 June 2005 transect. The reference elevation is 372.18 m. Ordinate = energy in volts and abscissa = bin number (bin spacing = 1 ns).



Analysis of ICESat transects across the lake demonstrates that the shots from the land to water could be divided into four categories:

- Category 1: Shots corresponding to land. The saturation correction is valid (between 0 and 1.50 m).
- Category 2: Three to eight shots correspond to “land”, “land+water” or “water” with invalid correction.
- Category 3: Two to ten shots correspond to “water” with valid correction, but not adapted (called transition shots).

- Category 4: ICESat shots corresponding to "water" with estimated elevations close to reference elevations. The saturation correction is valid and well adapted.

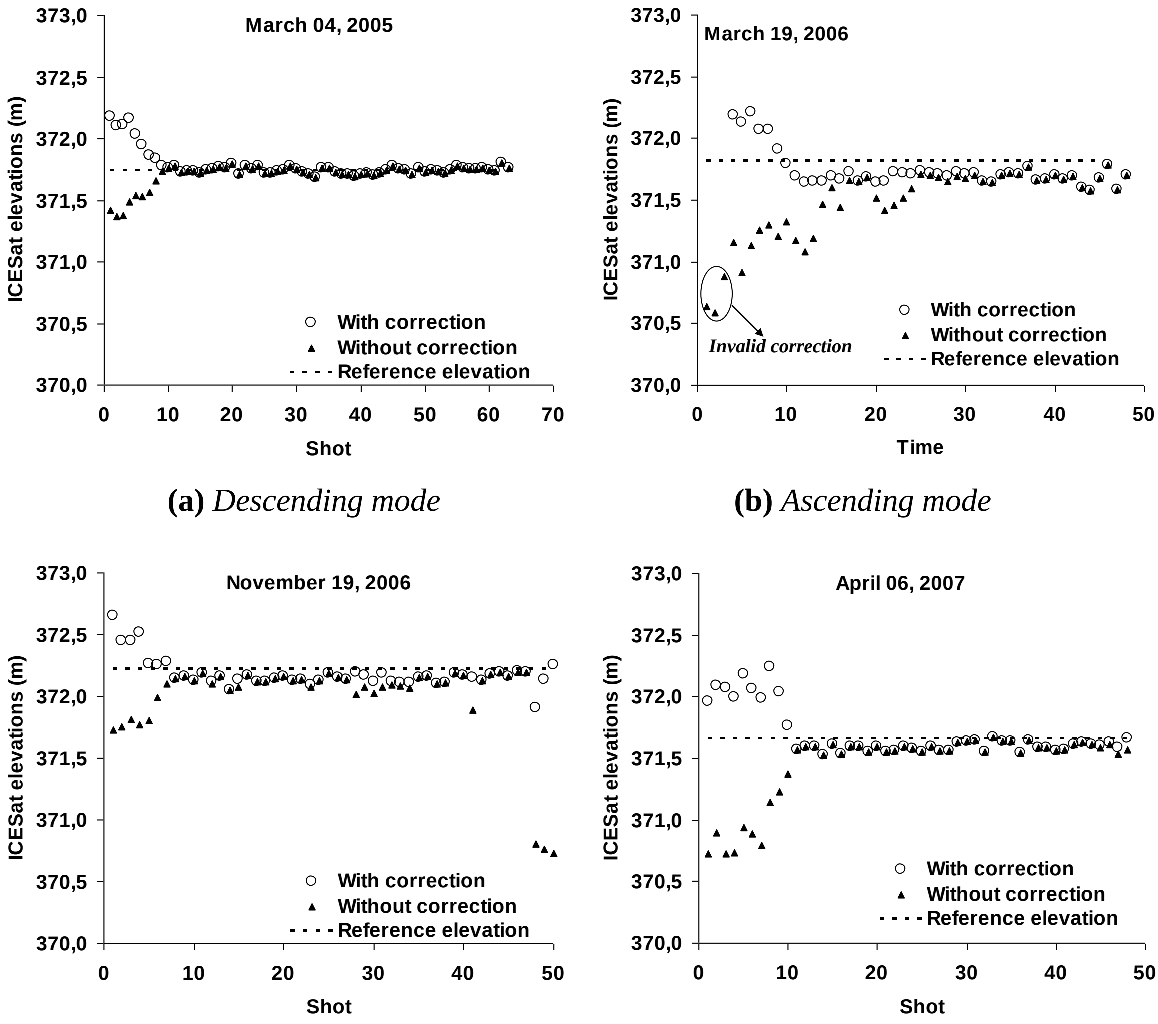
On the passage of ICESat from land to water, the first laser waveforms corresponding to water exhibit a strong saturation. The elevation of theses shots systematically exhibit a significant variation compared to the reference elevation (Figure 4). Indeed, GLAS elevations of water surfaces without saturation correction are lower than reference elevations from −40 to −90 cm (maximum values). With correction of the saturation effect, elevations are higher than reference elevations from +20 to +50 cm (maximum). The highly saturated elevations without available correction (−999.00) are lower than the reference elevation of approximately one meter (Figure 4(b)). This saturation phenomenon which affects 2 to 10 spots is more important in ascending mode than in descending mode. The instrumental parameters are not different in ascending and descending modes. Shots following the first saturated waveforms provide elevations very close to the reference elevation with weak fluctuations. However, the analysis of the terrain geometry shows that the transition land-lake in ascending mode is very different from the transition land-lake in descending mode. In the South, when the Haute-Savoie massif is thrown into the lake, the transition land-lake in ascending mode is brutal with uneven of 550 m on a distance of 5 km. Conversely, in the Lausanne area in North, the transition land-lake in descending mode is softer with uneven of 260 m on 5 km. The difference in the observations between ascending and descending transects could be related to the laser beam target reflectivity.

Saturation is due to specular reflection of the water that saturates the detector, depending on laser beam target reflectivity. ICESat profiles demonstrate that a certain time is necessary for the gain control to compensate for electronic saturation by a reduction of gain. This could explain the progressive return to normal that can last for 10 measurements (maximum duration of 0.25 seconds and a maximum distance about 1.5 km). Moreover, the time necessary for desaturation of the detector depends on the ICESat pointing angle. Pointing angles larger than nominal will reduce the probability of waveform saturation but will increase the elevation error. The relationship between the pointing angle (θ) and the elevation error (ε) is given by $K.\alpha\ \theta$ [12], where K is a constant = 5cm/ °/arcsecond and α is the pointing knowledge error in arcseconds. For our ICESat dataset, the pointing angle was close to 0.3 °(nominal value). For α for a fully-calibrated laser campaign is = 1.5 arcseconds (L3a laser campaign), the elevation error ε = 2.25 cm.

This slowness in adaptation of gain after the land-water transition phase seriously limits the ICESat for limnimetric monitoring of rivers. With the exception of great rivers, the detector has not enough time after each land-water transition to correctly adjust the saturation correction coefficient. With or without correction, the first estimates of ICESat elevations would have an altimetric error of several tens of centimeters.

The 19 March 2006, transect demonstrates successively the first shots of the transition slightly saturated (valid correction), oversaturated (not valid correction = −999.00), and then slightly saturated (valid correction) (Figure 4(b)). This alternation of "valid correction" and "not valid correction" is surprising. There can be a restitution error for the spot position on the ground related to pointing error. Alternatively, the laser direction can oscillate to approach nadir in certain cases resulting in saturation, whereas the pointing angle is sufficient to avoid saturation in other cases. This second scenario would explain the nonsystematic nature of the phenomenon.

Figure 4. Some examples of ICESat transects in comparison to reference elevation (gauges). Abscissa = shot number (spacing = 0.025 s) and ordinate = elevation (ICESat with/without saturation correction, and hydrological gauges).



(a) *Descending mode* **(b)** *Ascending mode*

(c) *Ascending mode* **(d)** *Ascending mode*

Table 1 summarizes the results of the comparison between GLAS elevations (GLA14 product) and lake level data recorded by hydrological stations. The mean lake height for each ICESat transect is determined from averages of all valid height measurements. The mean value difference between the ICESat and reference elevations varies from 0 to 1.09 m for GLAS data without the correction of saturation effect and from 0 to 22 cm for corrected data. The RMS error ranges from 5 cm to 1.19 m without correction and from 5 cm to 30 cm with correction (Table 1). For nine ICESat tracks, the RMSE is greater than 20 cm when the correction is not applied against 2 tracks (Table 1). The mean RMSE for all tracks is approximately 15 cm with the saturation correction and 5 cm excluding transition footprints (first saturated waveforms). The errors are higher when the saturation correction is not applied (33 cm). Transects acquired on 13 March 2008, and 6 April 2007, had high standard deviations in comparison to other transects, which could result from a lack of sufficient correction for atmospheric effects. For the 13 March 2008 transect, only 22 data were used in the accuracy calculation. This result from implementing the saturation correction for continental waters corroborates the previous observations of Urban *et al.* [12].

Table 1. Comparison of Geoscience Laser Altimeter System (GLAS) and reference elevations (hydrological gauges) for Lake Leman. The eight dates marked by a star (*) have weak or null saturation corrections.

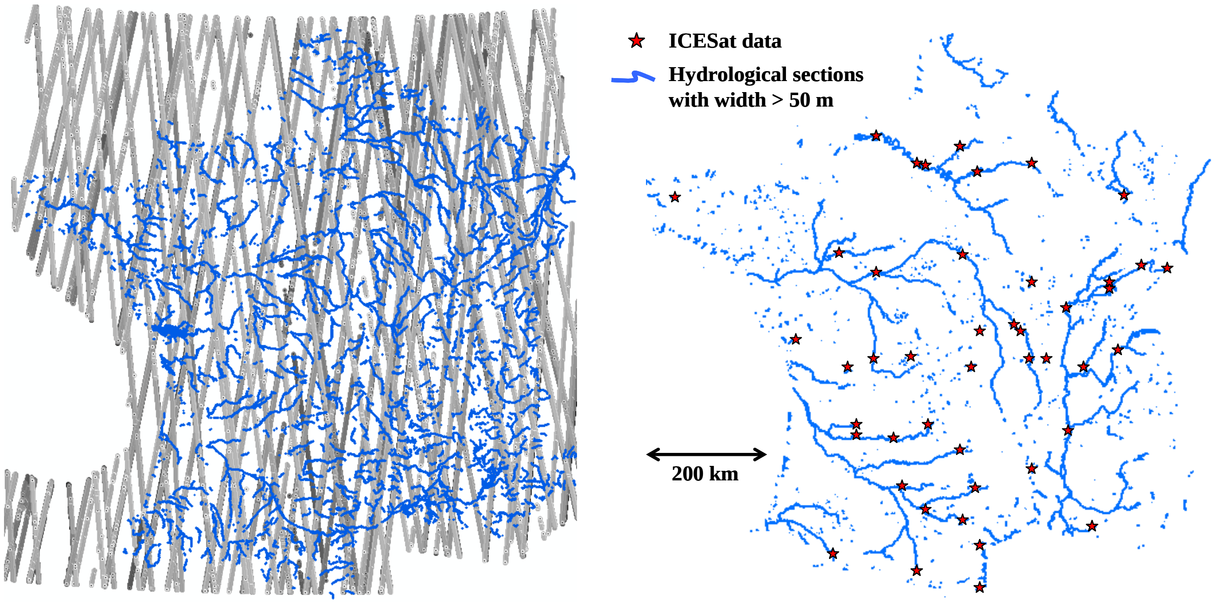
Date	Hydrological gauges	ICESAT Dataset	ICESat elevation (m) Without correction				ICESat elevation (m) With correction			
dd/mm/yy	Reference elevation (m)	Shot number	mean	std	RMSE	ICESat-Ref	mean	std	RMSE	ICESat-Ref
02/03/04 *	371.72	60	371.72	0.05	0.05	0.00	371.72	0.05	0.05	0.00
12/06/04 *	372.23	47	372.19	0.11	0.11	−0.04	372.24	0.12	0.12	0.01
04/03/05 *	371.74	61	371.78	0.11	0.12	0.04	371.71	0.09	0.09	−0.03
16/03/05	371.68	42	370.59	0.50	1.19	−1.09	371.77	0.16	0.18	0.09
03/06/05	372.18	61	371.49	0.59	0.90	−0.69	372.14	0.09	0.10	−0.04
15/11/05 *	372.25	49	371.99	0.10	0.27	−0.25	372.05	0.13	0.23	−0.19
19/03/06	371.82	43	371.53	0.22	0.36	−0.29	371.74	0.15	0.17	−0,08
07/06/06 *	372.17	63	372.24	0.07	0.10	0.07	372.26	0.08	0.12	0.09
18/06/06	372.26	45	372.19	0.21	0.22	−0.07	372.42	0.11	0.19	0.16
07/11/06 *	372.22	63	372.23	0.13	0.13	0.01	372.29	0.08	0.11	0.07
19/11/06	372.22	50	372.00	0.34	0.40	−0.22	372.18	0.12	0.13	−0.04
25/03/07 *	371.74	61	371.81	0.10	0.12	0.07	371.87	0.07	0.15	0.13
06/04/07	371.66	48	371.45	0.28	0.35	−0.21	371.69	0.19	0.19	0.03
16/10/07	372.21	59	372.02	0.24	0.30	−0.19	372.20	0.07	0.07	−0.01
13/03/08 *	371.53	22	371.31	0.21	0.30	−0.22	371.31	0.21	0.30	−0.22

3. Rivers of Metropolitan France

The accuracy of GLAS elevations was then studied using data acquired for French rivers wider than the size of ICESat footprint (Figure 5(a)). This comparison allows for analysis of the accuracy of GLAS measurements for rivers and to conclude on the use of ICESat for these small bodies of water. Only GLAS data from laser number 3 (campaign L3) were used because this area had the smallest major axis footprint size (approximately 55 m compared with 90 m for L2 and 149 m for L1), which is better adapted to the width of the French river. 10 ICESat data collection campaigns were used (L3A to L3J) (Table 2). All selected ICESat footprints had the following characteristics: (1) intersecting rivers with a width greater than 50 m, (2) radius of 1 km for gauge stations with a well referred limnimetric scale, and 3) distance far enough from hydraulic systems that can disrupt the water level within a small distance. Moreover, optical aerial photos were used to validate the selection of ICESat footprints. For this comparison, 26 ICESat tracks and 46 footprints were obtained (Figure 5(b)). This weak number for ICESat measurements illustrates the difficulty of monitoring small rivers with the ICESat configuration.

Assuming that measurements at gauge stations were of sufficient accuracy regardless of distance in time and space between GLAS shot and gauge station measurement, the elevation of each GLAS shot was then compared with the one from the closest hydrological station at the closest measured time. For this latter point, the obtained mean deviation between the time of GLAS acquisitions and the stations was 1.8 hours with a standard deviation (std) of 2.25 hours.

Figure 5. (a) ICESat tracks (in gray) and French hydrographic network (in blue), **(b)** GLAS data used in this study (rivers width >50 m, far from any dam or other hydraulic plant, with distance between ICESat shot and hydrological stations <1,000 m).



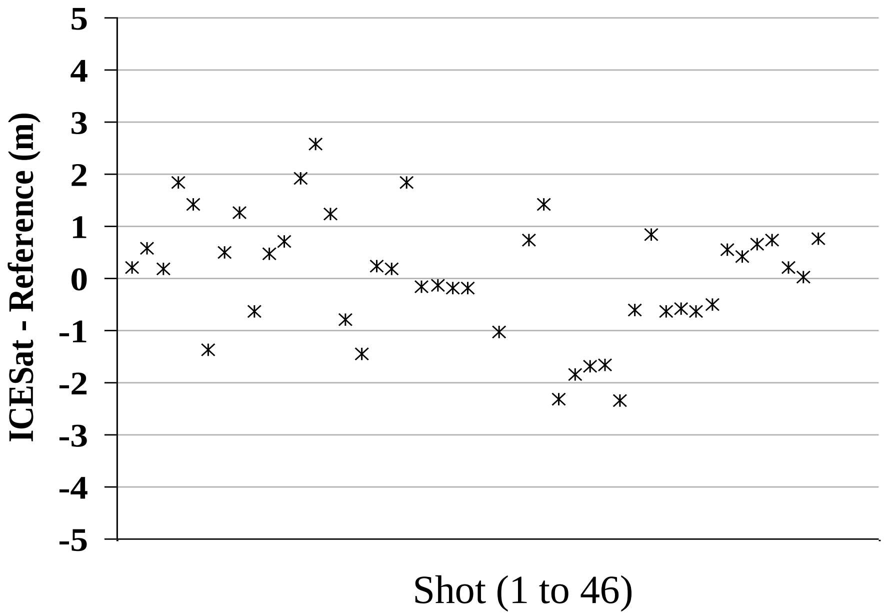
(a) (b)

Table 2. Start date and End date of ICESat campaigns L3A to L3J.

Laser campaign	Start date (dd/mm/yyyy)	End date (dd/mm/yyyy)
L3A	10/03/2004	11/08/2004
L3B	02/17/2005	03/24/2005
L3C	05/20/2005	06/23/2005
L3D	10/21/2005	11/24/2005
L3E	02/22/2006	03/28/2006
L3F	05/24/2006	06/26/2006
L3G	10/25/2006	11/27/2006
L3H	03/12/2007	04/14/2007
L3I	10/02/2007	11/05/2007
L3J	02/17/2008	03/21/2008

The RMSE for GLAS elevations obtained on the French rivers is 1.14 m (bias = 0.07 m; std = 1.15 m; 46 footprints) (Figure 6). This corresponds to approximately 10 times the RMSE for wider bodies of water, such as Lake Leman. For concerned ICESat waveforms, 61% were saturated and the correction of this saturation was not possible (correction = −999,000). Moreover, the correction proposed for the first water shots following the passage of ICESat from land to water is not appropriate (data before correction are underestimations, while data after correction are overestimations). The difference between the errors observed for Lake Leman in comparison to French rivers is close to the results that Birkett obtained with altimetry radar for Lake Chad [8] and rivers in the Amazon basin [5].

Figure 6. Difference between GLAS and hydrological stations elevations (reference) for French rivers. Each point corresponds to one footprint (for a total of 46 footprints).



4. Conclusions

GLAS elevation precision for Lake Leman was similar to previously published values in the literature (RMSE between 5 and 30 cm with a mean value of approximately 15 cm). The saturation correction for GLAS elevation was necessary for consequent improvement of error (bias, RMSE). A precision greater than 15 cm for GLAS elevation was possible for bodies of water greater than 1.5 km. Indeed, the first ten footprints for only water after passage of laser from land to water are often saturated with an inappropriate saturation correction. These results demonstrated that several GLAS measurements are necessary to ensure that the GLAS system provides reliable saturation correction. GLAS temporal profiles reveal a slow progressive adaptation of the GLAS sensor before correct elevations can be proposed. This adaptation can reach 0.25 s (10 shots). Therefore, elevation measurements performed for the first hundred meters, which follow the land-water transition, are biased. For example, this adaptation distance is approximately 1.5 km for ten transition shots.

The GLAS precision was then evaluated for data acquired from rivers in France. The determined RMSE was 1.14 m (bias ± std = 0.07 m ± 1.15 m). This result demonstrates the difficulty of using GLAS data for rivers that are relatively smaller in width (inappropriate saturation correction).Therefore, a factor of 10 was determined for the GLAS precision between large lakes and small rivers.

The computed accuracy for ICESat water elevation data can make these data inconsistent depending on their hydrological use. When using water levels data to monitor the dynamic of water balance for large reservoirs, assimilation of water levels data with a metric accuracy can reduce errors of estimated water balance by a factor of two [19]. But according to studies on fluvial hydraulic simulation model performances, the computed accuracy for ICESat water elevation is of poor interest [20]: for flood modeling in Europe occurring typically in low slopes fluvial environments, a decimeter accuracy of observed water levels, consistent with hydraulic output accuracies and fluvial slopes is required [21]. Assimilation of data with only decimeter accuracy adds meaningful value to hydraulic modeling, especially if this data is not frequent in space [22], which is the case of ICESat data.

Moreover, as the accurate ICESat measurements require significant water body width (hundreds of meters), the ICESat water level measurements are only adapted to major rivers and large catchment scales, or flood plains during extreme events.

Acknowledgements

The authors would like to thank the ICESat team and the National Snow and Ice Data Center for providing ICESat data and expertise. The authors would also like to thank the French National Water Observation Service "EauFrance" for providing access to the national gauge database.

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